REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
22-09-2006

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
July 1, 2001 – June 30, 2006

4. TITLE AND SUBTITLE

A unified brain architecture for perception and cognition

with applications to information processing technology

5a. CONTRACT NUMBER

5b. GRANT NUMBER
AFOSR F49620-01-1-0423

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT

AFRL-SR-AR-TR-06-0446

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approve for Public Release: Distribution Unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT Research at Boston University has produced computational models of biological vision and learning that embody a growing corpus of scientific data and predictions. Vision models perform long-range grouping and figure/ground segmentation, and memory models create attentionally controlled recognition codes that intrinsically combine bottom-up activation and top-down learned expectations. These two streams of research form the foundation of completed projects that define novel dynamically integrated systems for image understanding. Simulations using multi-spectral images illustrate road completion across occlusions in a cluttered scene, information fusion from input labels that are simultaneously inconsistent and correct, and applications of models of color vision. The CNS Technology Lab has further integrated science and technology through analysis, testing, and development of cognitive and neural models for large-scale applications, complemented by software specification and code distribution.
Technology transfer: http://cns.bu.edu/techlab/modlules/techtransfer

15. SUBJECT TERMS
Information fusion, Image analysis, Data Mining, Neural networks, Adaptive Resonance Theory (ART), ARTMAP, Computational vision, Color vision, BCS/FCS, Remote sensing, Geographic Information Systems, Technology transfer

16. SECURITY CLASSIFICATION OF: unclassified			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
unclassified	unclassified	unclassified	none	14	

FINAL TECHNICAL REPORT
July 1, 2001 – June 30, 2006
AFOSR F49620-01-1-0423

Information fusion for image analysis: Neural methods and technology development

Air Force Office of Scientific Research, Chemistry and Life Sciences Directorate
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Program on Information Fusion (Topic: Information Fusion for Image Analysis), under the Partnerships for Research Excellence and Transition (PRET)

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ABSTRACT

Research at Boston University has produced computational models of biological vision and learning that embody a growing corpus of scientific data and predictions. Vision models perform long-range grouping and figure/ground segmentation, and memory models create attentionally controlled recognition codes that intrinsically combine bottom-up activation and top-down learned expectations. These two streams of research form the foundation of completed projects that define novel dynamically integrated systems for image understanding. Simulations using multi-spectral images illustrate road completion across occlusions in a cluttered scene, information fusion from input labels that are simultaneously inconsistent and correct, and applications of models of color vision. The CNS Technology Lab has further integrated science and technology through analysis, testing, and development of cognitive and neural models for large-scale applications, complemented by software specification and code distribution.
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RESEARCH PROJECTS

INFORMATION FUSION AND HIERARCHICAL KNOWLEDGE DISCOVERY BY ARTMAP NEURAL NETWORKS (Siegfried Martens, Ogi Ogas, Santiago Olivera, Gail Carpenter)

Image fusion has been defined as "the acquisition, processing and synergistic combination of information provided by various sensors or by the same sensor in many measuring contexts." (Simone et al., 2002, p. 3) When multiple sources provide inconsistent data, such methods are called upon to select the accurate information components. As quoted by the International Society of Information Fusion: "Evaluating the reliability of different information sources is crucial when the received data reveal some inconsistencies and we have to choose among various options." For example, independent sources might label an object *beach* or *road* or *river*. A fusion method could address this problem by weighing the confidence and reliability of each source, merging complementary information, or gathering more data. In any case, at most one of these answers is correct.

This project has introduced a novel approach to the information fusion problem, with new methods that derive consistent knowledge from sources that are paradoxically both inconsistent and accurate. This is a problem that the human brain solves well. A young child who hears the family pet variously called *Spot*, *puppy*, *dog*, *dalmatian*, *mammal*, and *animal* is not only not alarmed by these conflicting labels but readily uses them to infer functional relationships that are almost never explicitly specified. An analogous information fusion problem seeks to classify the terrain and objects in an unfamiliar territory based on intelligence supplied by several reliable sources. Each source labels a portion of the region based on sensor data and observations collected at specific times, and based on individual goals and interests. Different sources might label a given pixel *beach*, *plage*, *open space*, and *natural*. A human mapping analyst would, in this case, be able to apply a lifetime of experience to resolve the paradox by organizing objects in a knowledge hierarchy, and a rule-based expert system could be constructed to codify this knowledge. Alternatively, an analyst might be faced with complex or unfamiliar labels, and the structure of label relationships might vary from one test region to the next.

An ARTMAP neural network can derive hierarchical knowledge structures from nominally inconsistent training data (Carpenter, Martens, & Ogas, 2005). The system learns that disparate pixels map to the output class *beach*; but, if similar or identical pixels are, at other times, labeled *plage* or *open space* or *natural*, the system learns to associate multiple classes with a given input. Testbed image examples have shown that the overall pattern of distributed predictions can reveal a knowledge hierarchy which guides the production of consistently layered maps of test regions. Even though no inter-class relationships are specified during training, the system uses distributed activation patterns of learned codes to derive knowledge of relationship rules, confidence estimates, equivalence classes, and hierarchical structures (Figure 1).

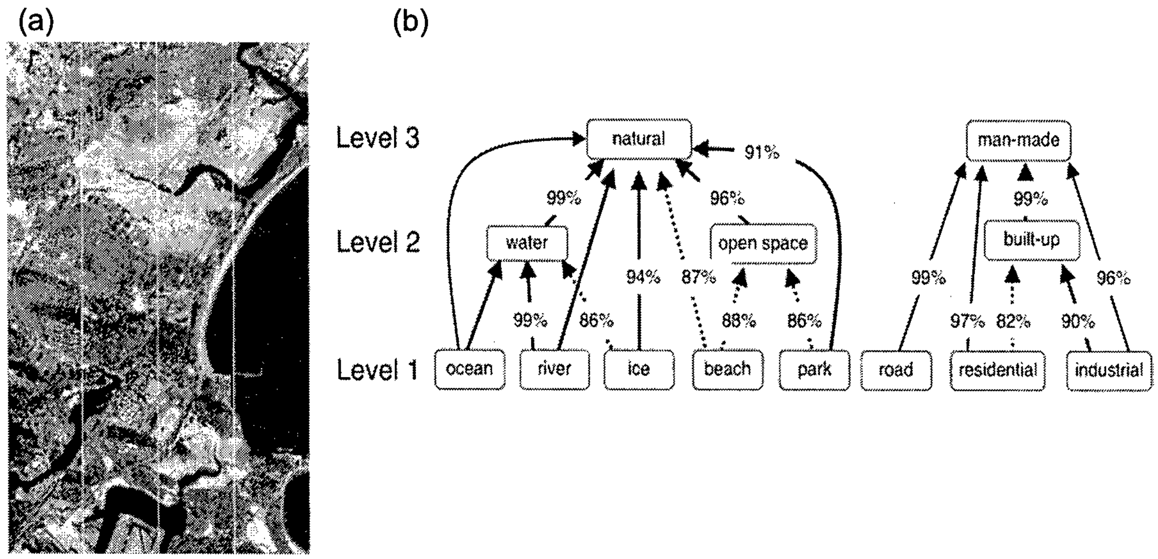

Figure 1: (a) Boston testbed image, 5.4km x 9km. Input bands: Landsat (30m), panchromatic (15m), and thermal (60m). The image is divided into four vertical strips: two for training, one for validation (if needed), and one for testing. This protocol produces geographically distinct training and testing areas, to assess regional generalization. Typically, class label distributions vary substantially across strips, and ground truth is available for only a fraction of the training region. (b) For the Boston example, the ARTMAP fusion system correctly produces all class rules and levels. Rule confidence estimates appear beside the arrows.

CONFIGR (COntour FIgure GRound) MODEL FOR LONG-RANGE OBJECT COMPLETION AND FIGURE-GROUND SEGMENTATION (Chaitanya Sai Gaddam, Ennio Mingolla, Gail Carpenter)

In two ground-breaking 1985 articles (*Neural dynamics of form perception: boundary completion, illusory figures, and neon color spreading*; *Neural dynamics of perceptual grouping: textures, boundaries, and emergent segmentations*), Stephen Grossberg and Ennio Mingolla introduced the Boundary Contour System / Feature Contour System (BCS/FCS) model. Over the past two decades, the original model has been extensively developed and experimentally confirmed in the domains of biological vision and psychophysics, and aspects of the system have been implemented in technological applications. However, simulations of BCS/FCS properties have typically been limited to proof-of-concept examples, and the model's potential to realize the computational power of the human visual system has barely been tapped.

A new model called CONFIGR (CONtour FIgure GRound) exhibits many BCS/FCS capabilities within a system that performs well in a general-purpose image processing environment. CONFIGR efficiently and accurately carries out the visual functions of boundary finding, long-

range grouping, and filling-in of connected featural components. CONFIGR model analyses have also fed back to the science, introducing new hypotheses concerning key neural mechanisms of early vision.

An object completion testbed demonstrates CONFIGR computations, using an image previously developed for the analysis of information fusion, map production, and target recognition methodologies (Parsons & Carpenter, 2003). In Figure 2, a default ARTMAP system (Carpenter, 2003) provides class labels for individual pixels, based on local image data. Objects identified from such local data are typically incomplete. In particular, roads (red pixels) show large gaps, due, for example, to shadows or overhanging trees. This example demonstrates how the CONFIGR model fills in gaps in the road figure, starting with incomplete outputs produced by a pixel-based recognition system. CONFIGR meets the challenge of calculating correct long-range completions while avoiding spurious interactions. The algorithm also meets speed requirements for practical implementation with large-scale images.

The first complete CONFIGR system operates on square binary pixels, which implicitly define a computational scale. At the pixel scale, operations of filling-in and figure-ground separation require only horizontal and vertical orientations. These two orientations nonetheless support long-range object completion at any orientation, since the completed figure may include the diagonal of an arbitrary rectangle (Figure 2). At larger scales, where the smallest independent units are pixel clusters, accurate object identification and figure-ground separation would require long-range completion across multiple orientations. Similarly, the analog pixel values of grey-scale, color, or multi-spectral images would require additional model development. Testbed applications also include digitizing paper maps and fault line identification from remotely sensed images. Figure 3 illustrates pilot study results for these sample applications.

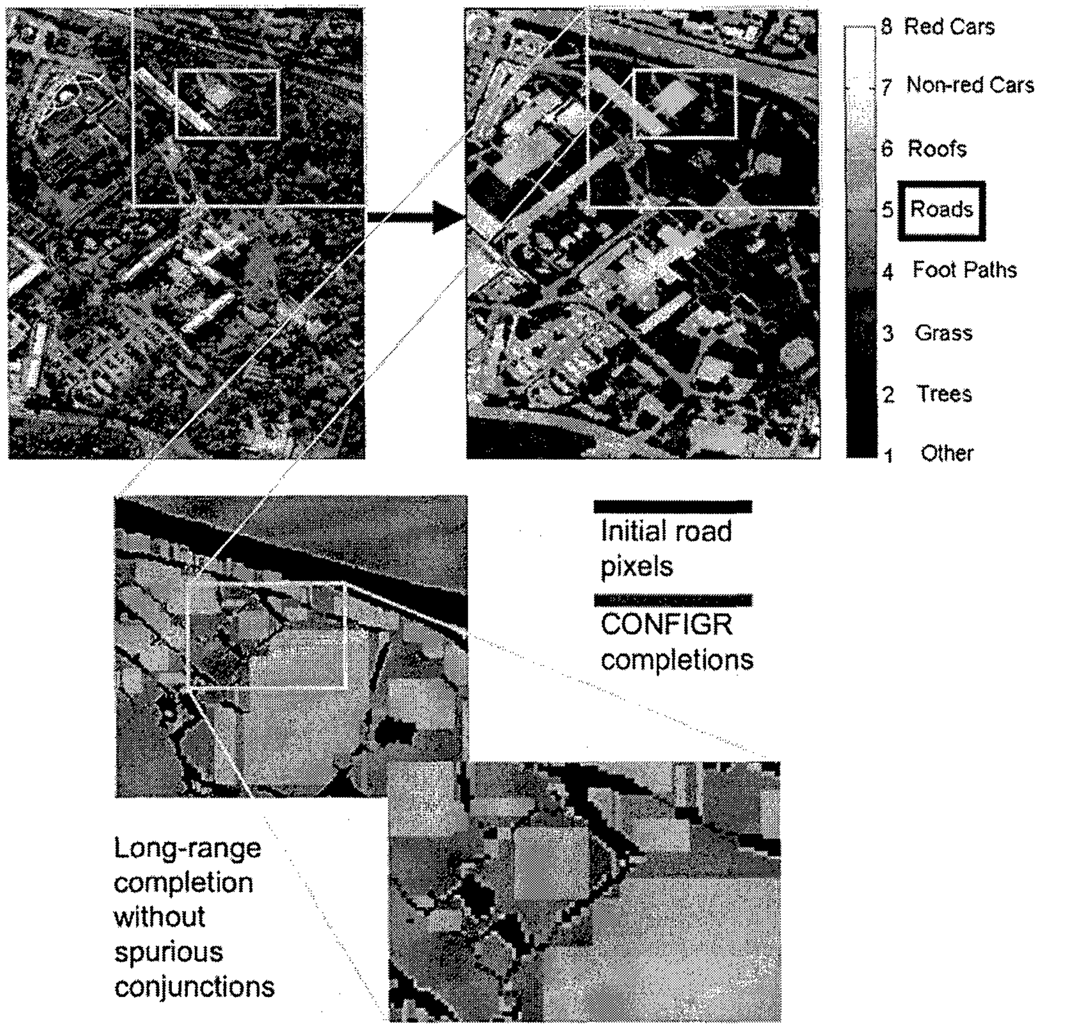

Figure 2: A default ARTMAP network maps image pixels to object classes. Figure pixels, identified from local sensor information, may produce gaps in structures such as roads (red) due, for example, to shadows or overhanging trees. The CONFIGR algorithm performs long-range figure completion (green). Complementary filling-in of ground pixels (light grey) blocks spurious figure conjunctions.

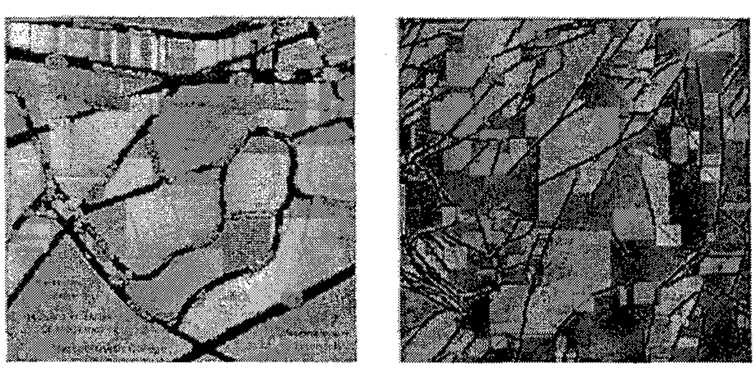

Figure 3: CONFIGR applications include digitizing paper maps and identifying geological structures from remotely sensed images. Pilot studies (illustrated here) have demonstrated the feasibility of these technology transfer areas.

DISCOV (DImensionless Shunting COlor Vision) MODEL: PHYSIOLOGY, IMAGE PROCESSING, AND CLASSIFICATION (Suhas Chelian, Ogi Ogas, Gail Carpenter)

The DISCOV (DImensionless Shunting COlor Vision) system models a cascade of primate color vision neurons: retinal ganglion, thalamic single opponent, and two classes of cortical double opponents (Figure 4) (Chelian & Carpenter, 2005). A unified model formalism derived from psychophysical axioms produces transparent network dynamics and principled parameter settings. DISCOV fits an array of physiological data for each neuron type, and makes testable experimental predictions (Figure 5). Pilot studies have demonstrated the marginal computational utility of each model neuron on recognition tasks.

Benchmark testbeds demonstrate DISCOV model contributions to image analysis. In particular, model color vision neurons respond selectively to small items embedded in fields of various types, as Figure 4 illustrates for red-green color channels. Image examples have been developed to test the hypothesis that DISCOV model neurons can draw attention to small target objects which might have been overlooked by more traditional image processing methods.

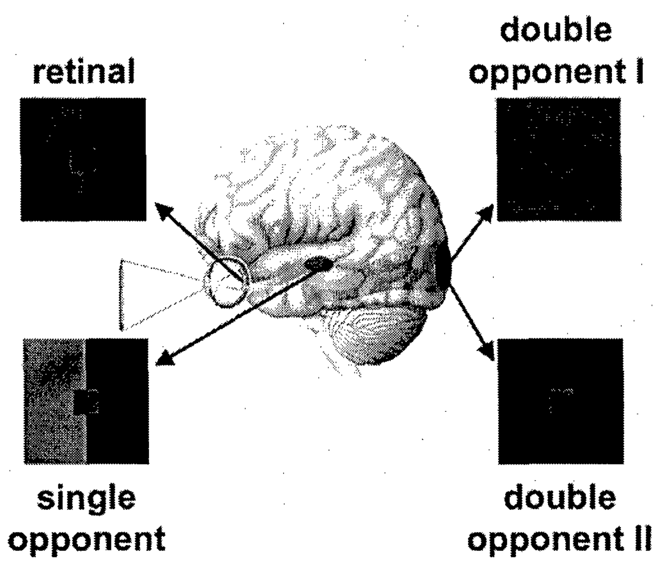

Figure 3: Preferred stimuli for color vision neurons in red ON-channels of the retina and for red-green channels of the thalamus (single opponent) and cortical area V1 (double opponent).

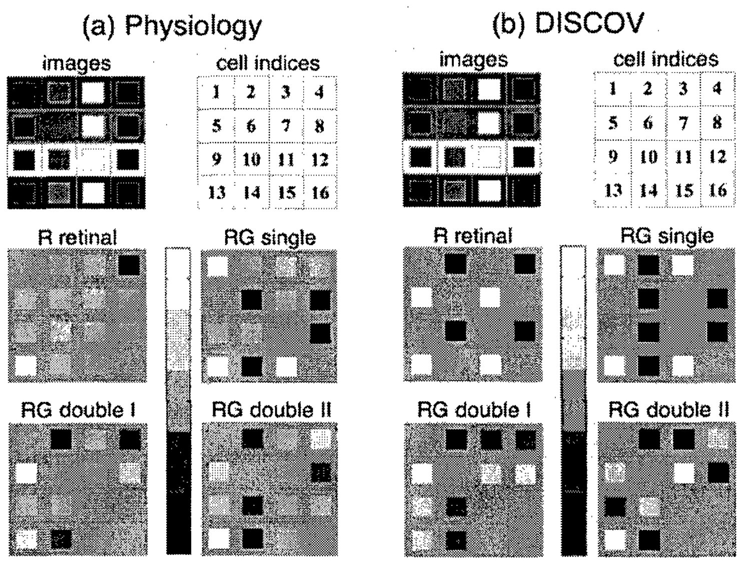

Figure 4: Center response profiles of color vision neurons (red retinal and red-green single opponent and double opponent I, II) from (a) physiology and (b) the DISCOV model. Elements of 4×4 *arrays in the top row indicate the center and surround images for 16 experiments for each neuron type. White images mix all colors maximally; black images have no color components. Response bins represent strong positive (white), intermediate positive, baseline, intermediate negative, and strong negative (black) activations, respectively. Orange center squares in (a) represent outcomes that are unreported in the experimental literature, and thus correspond to model predictions (b). Except for a reversal (in image cells 9 and 10) of reported double opponent II intermediate positive and negative responses, DISCOV matches all physiological data.*

METHODS FOR LARGE-SCALE DATA MINING: PREDICTING HIV RESISTANCE TO ANTIRETROVIRAL THERAPY (Timothy McKenna, Matthew Woods, Gail Carpenter; Harvard School of Public Health: Victor De Gruttola, Alex Macalalad; Brown University: Kenneth Mayer; Stanford University: Robert Shafer)

This project extends an ongoing interdisciplinary collaboration between CNS and medical faculty at the Harvard School of Public Health. The project has developed and compared methods, including regression, classification trees, and neural networks, to predict both clinical and *in vitro* HIV resistance to various antiretroviral therapies (phenotype) from a patient's genotype. CNS contributions include comparative analyses of neural network methods and the introduction and evaluation of data representations. The latter is enabling new consideration of the question of how the nature of a mutation affects drug responses, whereas previous representations were restricted to the location alone.

NEW BENCHMARK PROBLEMS FOR IMAGE ANALYSIS

This project has introduced three sets of image-based benchmark problems to enable the development of new systems for research projects funded by this grant. In order to promote technology transitions, comparative analyses, and further system development, testbed problems will be documented and posted on the web as part of the CNS Image Processing Toolkit.

(a) Mapping benchmarks

In collaboration with the Boston University Center for Remote Sensing: Farouk El-Baz (Director), Sucharita Gopal (Professor), Magaly Koch (Research Associate Professor)
http://www.bu.edu/remotesensing
CNS PhD students: Chaitanya Sai Gaddam, Arun Ravindran
Since the early 1990s, faculty from the Boston University Center for Remote Sensing and CNS have collaborated on projects that bring neural modeling methods to imaging problems. The challenges posed by these problems have also helped constrain and direct model development for technological applications in other domains. This project has developed challenge problems for figure-ground segmentation and rule discovery. Current topics of exploratory investigation include hyperspectral imagery and the problem of automatically digitizing paper maps.

(b) Biomedical imaging benchmarks

In collaboration with the Boston University Center for Biomedical Imaging: Dae-Shik Kim (Director)
http://www.bumc.bu.edu/Dept/Home.aspx?DepartmentID=420
CNS PhD student: Angela Chapman
A new collaboration between the Boston University Center for Biomedical Imaging and CNS is a rich source of multi-modal imagery and medical expertise. An initial study of image fusion methods is developing benchmark problems from magnetic resonance imaging (MRI) measurements, which produce data in at least five different modalities, each reflecting a different aspect of brain function or anatomy. Image fusion, rule discovery, and feature selection methods will be applied and further developed to integrate these layers of information. Since individual MRI subjects will be scanned monthly, this benchmark also presents the opportunity to develop methods for exploiting the temporal evolution of multi-modal data.

(c) Fenway image benchmark

CNS PhD students: Ogi Ogas, Santiago Olivera. High school intern: Timothy St. Clair
The website Massachusetts Geographic Information Systems (http://www.mass.gov/mgis/) provides many layers of state-wide imagery for public use. This site is the source of orthophoto data, at 0.5*m* resolution, for a new benchmark image called Fenway, selected to typify an urban setting (Figure 6). A companion registered LANDSAT image, at 30*m* resolution, facilitates the study of multi-scale vision and image processing systems. Ground truth identification, problem development, and evaluation are facilitated by the location of the CNS department within the designated area. This image has been developed to test model capabilities for directing attention to small objects such as cars in a scene.

Figure 6: The Fenway benchmark image (left) is a fragment of an orthophoto image of the Boston-area (right).

SOFTWARE DEVELOPMENT: CLASSIFIER SIMULATION MANAGER (CLASSER) AND THE CNS IMAGE PROCESSING TOOLKIT (CNS IPT) (Siegfried Martens, Ogi Ogas, Santiago Olivera, Timothy St. Clair, Ennio Mingolla, Gail Carpenter)

Whereas versions of ART and BCS models have been used in a wide variety of applications, many more systems that were developed primarily in the scientific context have been applied only to proof-of-concept examples. Current efforts in the CNS Vision and Technology Labs are seeking to bridge the gap between science and technology through analysis, testing, and development of system variations with a view to large-scale applications. This project complements these enterprises by focusing on the development and distribution of open-source software, in addition to collaborative research on new systems.

CLASSER (CLASSifier Simulation ManagER) is a new modular set of software tools that provide a user with classifier implementations while handling details of data management and collection of test results. CLASSER provides a high-level system interface for learning applications, allowing the user to work with entire data sets at a time instead of individual points, and automating the collection of output results. The software facilitates neural algorithm implementations in both the user's application setting and in the Leica Geosystems ERDAS IMAGINE environment. Downloads of Version 1.1 of CLASSER and its first interface, CLASSER Script, are now available:
http://profusion.bu.edu/techlab/modules/mydownloads/viewcat.php?op=&cid=49 .

The *CNS Image Processing Toolkit* (*CNS IPT*) is a modular set of Java tools that support the development of computational models based on the human visual system, as well as the analysis

and technology transitions of these models. Toolkit functions are complementary to and linked with the CLASSER software. The CNS Image Processing Toolkit currently exists as a pilot project (Figure 7). The Toolkit includes the testbeds developed projects funded by this grant, as well as a set of elementary test images to be used as consistent benchmarks for the development and comparative analysis of alternative methods.

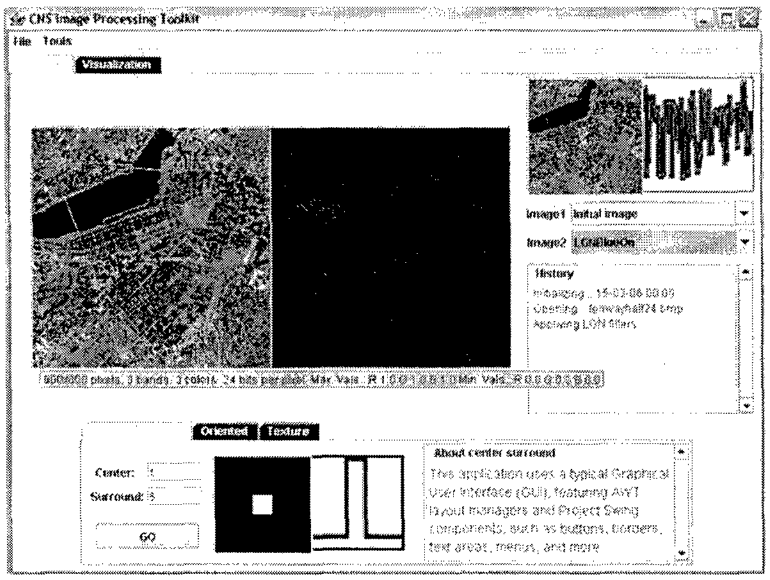

Figure 7: Development page from the CNS Image Processing Toolkit.

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